Geomagnetic Variations and Ionospheric Currents at Southern High Latitudes

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Abstract. Geomagnetic variations observed at three distances from the southern geomagnetic pole (at CGM latitudes -69.84°, -80.14° and -84.92°) are studied and differentiated for season, geomagnetic activity and magnetic local time. Results show that the increase in variations during the local summer season is less significant than the increase in variations associated with higher geomagnetic activity (with Kp 3). Moreover, variations larger than |50| nT occur more frequently at latitude -80.14°CGM than at latitudes -69.84° or -84.92° CGM, in particular during the local summer. The observations of D variations indicate that the ionospheric currents, both at -80.14° and -84.92° CGM, have their components along the line between each station and the eccentric dip_pole (located at about geographic latitude 66° S and longitude 129° E) oriented in the sunward direction. This is in agreement with previous observations of sunward polar cap current, here this is a quite frequent feature (with occurrence above 90%) for that specific components, independent of season and geomagnetic activity. In particular the sense of these ionospheric-current components' directions are also independent of the interplanetary magnetic field, which is well known to affect the direction of the total polar cap currents. The observations of the H variations at -69.84° CGM are in agreement with the expected auroral oval current pattern, indicating East-

West components of ionospheric currents mostly in the westward direction near magnetic local noon and in the eastward direction near magnetic local midnight sector. At latitudes -80.14° CGM, a reversal is observed for the East-West current components, in agreement with expected polar cap effects from the cusp and the auroral oval. A tendency for a second reversal for the East-West current components is seen at latitude -84.92° CGM, suggesting a rather structured, possible multi-cell, ionospheric current pattern in the southern polar cap.

Categories and Subject Descriptors: *(PACS) 94.30.-d Physics of the magnetosphere, 93.30.Ca Antarctica; (ACM) G.3 Probability and statistics.*

1. Introduction

Horizontal geomagnetic variations occurring at the highest latitudes can be directly related to 'equivalent' electric currents, i.e. the currents flowing in the perpendicular direction on the plane of a hypothetical spherical shell concentric to the Earth representing the ionosphere. In particular, at auroral latitudes (60°-70° CGM latitudes), the negative H-component geomagnetic variations (with respect to average, e.g., over a one-month period) are generally associated with westward ionospheric current components; the positive H-component geomagnetic variations are generally associated with the eastward ionospheric current components (e.g., Davis and Sugiura, 1966; and references therein). It is worth stressing that this statement refers to the specific ionospheric current component along the East - West direction, although the perpendicular components are also important for determining the direction of the total ionospheric current. Therefore this does not contradict observations of rapid changes with local time, latitude, or interplanetary magnetic field (IMF), or the expectation of a more or less sunward ionospheric current in the polar cap (Friis-Christensen et al., 1985).

The maximum intensity of the high-latitude ionospheric current distribution can be expected to be higher at nominal auroral oval latitudes than in the polar cap (e.g., Ballatore et al., 1998a; Ballatore et al., 2000). However previous comparisons did not consider each of the two perpendicular components separately. In addition, only the maximum positive and negative longitudinal geomagnetic variations at each UT (Universal Time) were taken into account for comparisons between polar cap and auroral oval latitudes, not all the observations at each station.

In order to study the intensity of the ionospheric currents at different distances from the geomagnetic pole, in this paper we compare 1-min geomagnetic variations from three locations spaced in latitude in the southern hemisphere. In particular both the H and D components of variations are taken into account separately, so that separate considerations about the East-West and North-South directions are possible. Specific attention is paid to the local times around magnetic noon and midnight, where the occurrence of the maximum eastward and westward current components are generally observed (e.g., Davis and Sugiura, 1966; Ballatore et al., 1998b).

Because the polar cap and cusp are geomagnetically connected to the external magnetosphere, closer to the interplanetary space, they respond to variations in the solar wind more rapidly than lower latitudes. Therefore individual observations show a high degree of variability in current directions and several statistical studies have been done to find more or less general repeated features, mostly based on the interplanetary magnetic field (IMF) orientation (Friis-Christensen and Wilhjelm, 1975). In particular, during times of southward interplanetary magnetic field (IMF), the ionospheric convection is determined by a typical two-cell convection pattern (Dungey, 1961; Akasofu et al., 1983; and references therein), so that at near-noon and near-midnight antisunward plasma flow and sunward currents are generally expected. In contrast, during times of northward IMF, the observation of anti-sunward currents in the near-noon region has been explained by the distortion of the two-cell pattern (Heppner and Maynard, 1987), while a four-cell convection can appear (Reiff and Heelis, 1994). In particular, Knipp et al. (1993) showed that the four-cell pattern is observed for $|Bz/By|>1$, while a distorted two-cell one occurs for $|Bz/By|<1$. Subsequent experimental observations have been mainly in agreement with these findings (e.g., Cumnock et al., 1995). In particular, between 10:30 MLT (magnetic local time) and 12:00 MLT, at about 84° magnetic latitude, for northward IMF with $|Bz/By|<1$, a large clockwise cell was observed by using ground-based magnetometer measurements (Huang et al., 2000).

Because of these multiple-cell current patterns, and because of their dynamical change with the interplanetary configuration, it is rather difficult to predict if geomagnetic variations will be mostly northward/southward or eastward/westward at any specific polar cap location. In the present work, we study the occurrence of North/South and East/West geomagnetic variations in order to find the possible recurrent features for the polar cap ionospheric currents.

2. Data Analysis and Experimental Observations

The data analyzed are 1-min resolution geomagnetic variations from the three Antarctic AGOs (Automatic Geophysical Observatories): P2, P1 and P6, whose coordinates are reported in Table I. The periods considered are, respectively, during the local summer, equinox and local winter and in particular: (a) from 36 to 56 DOY (Day Of the Year), (b) from 94 to 114 DOY and (c) from 200 to 220 DOY during 1997, in accordance with availability of simultaneous measurements from the all three stations.

For each one of the three periods, the data considered are the horizontal geomagnetic components H and D, respectively along the North-South (positive northward) and the East-West (positive Eastward) geomagnetic directions. It is important to mention that the geomagnetic south pole considered for the North-South and East-West directions is the eccentric dip pole (Fraser-Smith, 1987), located at geographic coordinates of about 66° S latitude and 128.5° E longitude. This figure also shows the locations of the AGO geomagnetic stations considered: P2, P1 and P6. The H and D variations have been computed by subtracting, respectively, the average H and D values calculated over the related 21-day interval of each period.

The distributions of the 1-min H and D variations are reported in Figure 2 separately for each station and each seasonal interval considered: Figure 2a is taking into account only geomagnetic quiet periods, with $Kp \leq 2$, while Figure 2b shows only the more disturbed periods with Kp ≥ 3. As expected, the occurrence of larger H and D variations is higher in Figure 2b than in Figure 2a, associated with the higher Kp. In addition, the percentage of occurrence of variations > |50| nT is higher during the local summer (top panels of Figure 2a and 2b) than during the local winter (bottom panels of Figure 2a and 2b), independent of the geomagnetic activity range considered. Moreover, the percentage of variations > |50| nT is maximum at P1, especially for the D component, independent of the season, and for the H component during the local summer. In particular, at P2 there is a small percentage of H variations that are: (a) >|100| nT during the local winter and for Kp ≤ 2; (b) > |400| nT during the equinox and for Kp ≥ 3. These very large ΔH occurrences are not observed at P1 and P6 and are evidently related to the auroral electrojets, whose location (about 60°-70° CGM latitude) is generally closer to P2.

Figures 3a (for Kp ≤ 2) and 3b (for Kp ≥ 3) show the distributions of the H and D variations, similarly to Figure 2a and 2b but for the specific time interval 9:00 - 15:00 MLT, around magnetic noon. Figure 3a shows that, for each season, the largest D variations are observed at P1, secondly at P6 and the smallest D variations are seen at P2. In contrast, the generally larger H variations are observed at P2, although during the local summer the percentage of the occurrence of ΔH > |50| nT is higher at P1 and secondly at P6. For each season, the signs of the H variations are mostly negative, i.e. geomagnetic southward (in the following, the variation direction is assumed to be in the geomagnetic system with the pole as the eccentric dip_pole when not otherwise specified) at P2, while these are more symmetrically distributed around zero for P1 and P6, with a tendency to be positive (northward) at both stations. The most recurrent feature in Figure 3a is the reversal of the sign of the D component variations, that are almost all negative (westward) for P1 and almost all positive (eastward) for P6. At P2 there is a tendency for the D variations to be mostly negative (similarly as for P1).

Similarly to Figure 3a, Figure 3b shows that the occurrence of the largest D is maximum at P1, secondly at P6 and minimum at P2, independent of the season. In addition the occurrence of the largest H is maximum at P2, secondly at P1 and minimum at P6. Regarding the direction of the variations, Figure 3b shows again the clear reversal of the D component between P1 and P6, here with a tendency for the P2 measurements to be in agreement with the P6 ones. Differently, the H component is mostly southward at P2, while the H distributions are more centered around zero for P1 and P6, with tendency to be mostly northward, especially for P1 during the local summer (top left panel). It is worth noting that, for Kp $\geq$ 3 and at time 9:00-15:00 MLT, the ΔH > 150 nT at P1 characterize the summer period, in fact these disappear during the local winter (in the bottom panel of Figure 3b).

Figure 4a (for Kp $\leq$ 2) and 4b (for Kp $\geq$ 3) show the distributions of the H and D variations, similarly to previous Figures but for the specific time interval 21:00 - 3:00 MLT, around local magnetic midnight. In Figure 4a the occurrence of the largest D is higher at P1, secondly at P6 and minimum at P2, similarly to Figure 3a. Differently than in Figure 3a, this is also true for the H component, with a percentage of occurrence close to 90% of ΔH < $|50|$ nT at P2. The sign of the D variation tends to be negative (westward) at P2, similarly to Figure 3a. Differently, the D variation signs at P1 and P6 are almost all opposite of Figure 3a (now respectively negative and positive). In addition, Figure 4a shows the reversal of the sign of the H variation with respect to Figure 3a: now mostly northward at P2 and southward at P1 and P6.

In Figure 4b, during high geomagnetic activity, the occurrence of the largest variations is maximum at P1 both for H and for D and at all seasons and the directions of the H variations are mostly southward at P1 and P6 and mostly northward at P2. This is similar to results in Figure 4a. Finally, in Figure 4b, the directions of the D components at P1 and P6 are, respectively, almost all eastward and westward (as in Figure 4a and opposite to Figure 3a and 3b).

3. Discussion

An enhancement in the horizontal geomagnetic variations is expected during higher geomagnetic activity, in particular at high latitudes (e.g., Ballatore et al., 1998c). At the same time, a sunlight increase of ionospheric conductivity is associated with the observation of higher geomagnetic variations during the local summer (e.g., Newell and Meng, 1988; Ballatore et al., 2000; and references therein). A direct comparison between the two effects can be obtained from Figures 2a and 2b: the difference in the amplitude of variations in the upper and the bottom panels of these Figures (showing the seasonal effect) is smaller than the difference between the corresponding upper panels in Figures 2a and 2b (showing the geomagnetic effect). Thus the geomagnetic activity influences these results more significantly than the season, at each of the considered stations.

Figures 2a and 2b illustrate that the largest H and D variations are observed at P1. Possible exception for the only negative H variations are observed: (a) for $Kp \geq 3$ at equinox period, (b) for $Kp \leq 2$ at local winter period. The occurrence of these higher variations at P1 than at P2 is not in opposition with the well known higher geomagnetic activity at auroral than at polar cap latitude, in fact these measurements do not cover the whole latitudinal circle at P1 and P2 latitudes. In particular, higher variations at P1 can be explained by its proximity to the cusp location, moving further from P1 and closer to P2 during the equinoxes and winter than it is during the summer (e.g., Newell and Meng, 1989; Ballatore et al., 1998c). This is in agreement with results reported in Figure 3a and 3b, for data corresponding to 9:00-15:00 MLT, just near the cusp location. For the specific intervals with $Kp \geq 3$, Figure 3b shows the presence of largely positive H variations during the local summer at P1, which disappear at winter, reasonably associated with the cusp movement. In particular, a shift of the cusp location towards higher geomagnetic latitudes is also expected during quieter geomagnetic conditions (e.g, Kamide et al., 1976). The effect of this shift is not as evident as the seasonal shift effect in our data. It is of interest to note that the occurrence of variations $>|50|$ nT is the highest at P1, then at P6 and the minimum at P2.

Further observations can be related to the occurrence of ionospheric currents associated with the H and D variations. Specifically the negative (positive) H variations are associated with the westward (eastward) component of the ionospheric equivalent currents and the negative (positive) D variations are associated to their southward (northward) components (e.g., Davis and Sugiura, 1966; Akasofu et al., 1983). In the present case the MLT is calculated with respect to the CGM pole (that is the eccentric dipole axial pole), while the H and D variations are calculated with respect to the eccentric dip_pole (close to DRV station in Figure 1), which rotates with UT in the MLT system.

In this coordinate system, a very recurrent reversal (almost 100% of data points) in the sign of the D variations is observed between P1 and P6, both at near-noon and near-midnight MLT. When each station is near-noon MLT, the negative D variations at P1 indicate that the ionospheric-current component along the P1/dip_pole is directed towards the south pole and the positive variations at P6 indicate that the ionospheric-current component along the P6/dip_pole is directed away from the south pole. At P1 MLT=LT-04:54, and at P6 MLT=LT-06:14. Therefore, looking at Figure 1, we see that the current component along P1/dip_pole is sunward when P1 is near noon MLT and also that the current component along P6/dip_pole is sunward when P6 is near noon MLT. Similarly, considering results in Figure 4a and 4b, the ionospheric current component above P1 along the directions P1/dip_pole is sunward when P1 is near midnight MLT, and the same is true for P6 along the P6/dip_pole direction. The conclusion is that, during the periods considered, at each polar cap location there is a component of the ionospheric currents that flows in the sunward direction along the line between the dip_pole and the location itself.

In order to investigate possible association between the occurrence of the D-component geomagnetic reversal and specific IMF orientations, we have verified the occurrence of both positive and negative IMF Bz and By for the intervals included in each of the histograms in Figure 3a, 3b and 4a, 4b. In addition, also the ratio |Bz/By| is at times higher and at times smaller than 1. In fact we see that the characteristics of the sign of the D-component geomagnetic variations at P1 and P6 have a recurrence above 90% in our observations. Moreover, the same results are observed during the geomagnetic quiet periods (for Kp ≤ 2) and during the disturbed ones (for Kp ≥ 3), respectively in Figure 3a/4a and in Figure 3b/4b.

It is worth noting that the P1/dip_pole and the P6/dip_pole directions are not parallel and neither of them is parallel to the sunward-antisunward direction. Therefore these results, and in particular the relative independence of this component from the IMF, do not disagree with previous convection patterns reported, e.g., by Friis-Christensen et al. (1975; 1985). In fact the differences can be explained in terms of the effect of the components perpendicular to these directions P1/dip_pole and P6/dip_pole.

Figures 3a and 3b show that the East-West component of the ionospheric currents above P2 is generally westward (negative ΔH), with an increase of the northward (positive ΔD) component during the most geomagnetic disturbed intervals. On the contrary (from Figure 4a and 4b) this East-West component is mostly eastward (positive ΔH) for time 21:00-03:00 MLT, again with an increase of the northward (positive ΔD) component during higher Kp. These findings are in agreement with previous observations of morning westward and evening eastward auroral oval ionospheric current components (e.g., Hughes and Rostoker, 1979). Moreover, the present higher northward component of currents might suggest a possible agreement with the expected move of auroral features towards lower latitudes during higher geomagnetic activity (Kamide et al., 1976).

Regarding the H components at P1 and P6, the direction of the variations is not so definite in sign. Most of the H variations are positive in the day side and negative in the night side at both stations. Considering that a positive ΔH near noon at P1 corresponds to a negative ΔH at the same MLT at P6, this result indicates a reversal of the East-West current component between latitude 80.14°S (P1) and 84.92°S (P6), both at near-noon and near-midnight MLT intervals. A similarly frequent reversal of the East-West ionospheric current components, is also observed between P2 and P1 latitudes, so that there is a tendency to have the same sign above P2 and P6. This P2-P1 reversal in the East-West current components is in agreement with the expected presence of return currents in the polar cap from the auroral oval and cusp region. Moreover, the reversal observed between P1 and P6 is in agreement with previous observations of structured multi-cell convection pattern above the polar cap, with return currents from P1 over P6 and/or possible different current cells above the two locations (Knipp et al., 1993; Huang et al., 2000).

4. Summary and conclusions

Due to the connection with the most external magnetospheric shells, the high-latitude parameters change dynamically with interplanetary space configuration. In particular, enhancements of the horizontal geomagnetic variations are expected during periods of high geomagnetic activity and during local summer, due to the increase in the ionospheric conductance (e.g., Ballatore et al., 1998c). In the present results, these enhancements are shown at each one of the three considered stations P2, P1 and P6. In particular, the geomagnetic activity level affects the geomagnetic variations much more significantly than the season, at all latitudes from the upper boundary of the auroral oval (P2 station) to the near-pole geomagnetic latitudes (P6 station).

Comparisons among the considered stations show that the occurrence of variations larger than |50| nT is maximum at P1, with possible exception for the only H variations (in particular in the near-noon MLT), tending to be the largest at P2 during the local winter. This is interpreted in terms of the proximity of P1 (-80.14° CGM latitude) to the cusp location, which is expected to shift toward lower latitudes (further from P1 and closer to P2) during the local winter (Newell and Meng, 1988).

Taking into account the association between geomagnetic variations and equivalent ionospheric currents, the feature identified as the most recurrent one (independent of the IMF orientation) is a sunward current component along the direction between each polar cap station and the dip_pole. This feature is observed both at P1 and P6 and during both near-noon and near midnight MLT. This can be related to the presence of the well known polar cap sunward current (Friis-Christensen et al., 1985), however this is a more recurrent feature (with occurrence close to 100%), independent of the IMF, suggesting a simple way of predicting the expected direction of at least the sign of this specific current component above each polar cap location.

In addition, the East-West ionospheric current component above P2 is mostly westward in the dayside and eastward in the nightside, in agreement with previous auroral oval observations (Hughes and Rostoker, 1979). The occurrence distribution of these current components is more centered around zero for P1 and P6, with a possible tendency to have opposite signs above P2 and P1, in agreement with the expected direction of polar cap return current from the auroral oval and cusp. A second East-West reversal is frequently observed between P1 and P6, suggesting a structured ionospheric current pattern, in agreement with return currents in the near CGM pole region from the lower latitude polar cap and possible multi-cell configurations.

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Figure Captions.

Figure 1. Location of the stations P2, P1 and P6; the solid square indicates the location of the eccentric dip_pole.

Figure 2. Percentage of the distributions of the H and D component variations for the specific periods indicated on the right at the AGO stations P2 (white columns), P1 (gray columns) and P6 (black columns). Figure 2a refers to intervals with $Kp \leq 2$ and Figure 2b refers to intervals with $Kp \geq 3$.

Figure 3. Percentage of the distributions of the H and D component variations for the specific periods indicated on the right at AGO stations P2 (white columns), P1 (gray columns) and P6 (black columns) for (9:00--15:00) MLT. Figure 3a refers to intervals with $Kp \leq 2$ and Figure 3b refers to intervals with $Kp \geq 3$.

Figure 4. Percentage of the distributions of the H and D component variations for the specific periods indicated on the right at the AGO stations P2 (white columns), P1 (gray columns) and P6 (black columns) for (21:00--03:00) MLT. Figure 4a refers to intervals with $Kp \leq 2$ and Figure 4b refers to intervals with $Kp \geq 3$.

Table I.

	Geographic Coordinates	Corrected Geomagnetic Coordinates	MLT at 00:00 UT
P2	85.67° S, 313.62° E	69.84° S, 19.33° E	3:29
P1	83.86° S, 129.61° E	80.14° S, 16.87° E	3:44
P6	69.51° S, 130.03° E	84.92° S, 215.39° E	14:26

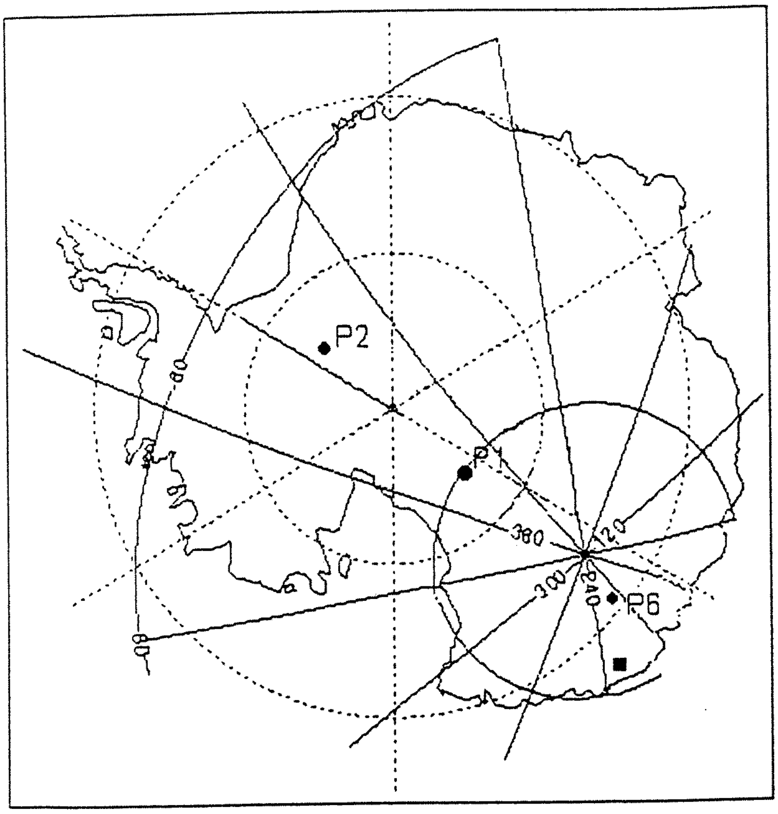
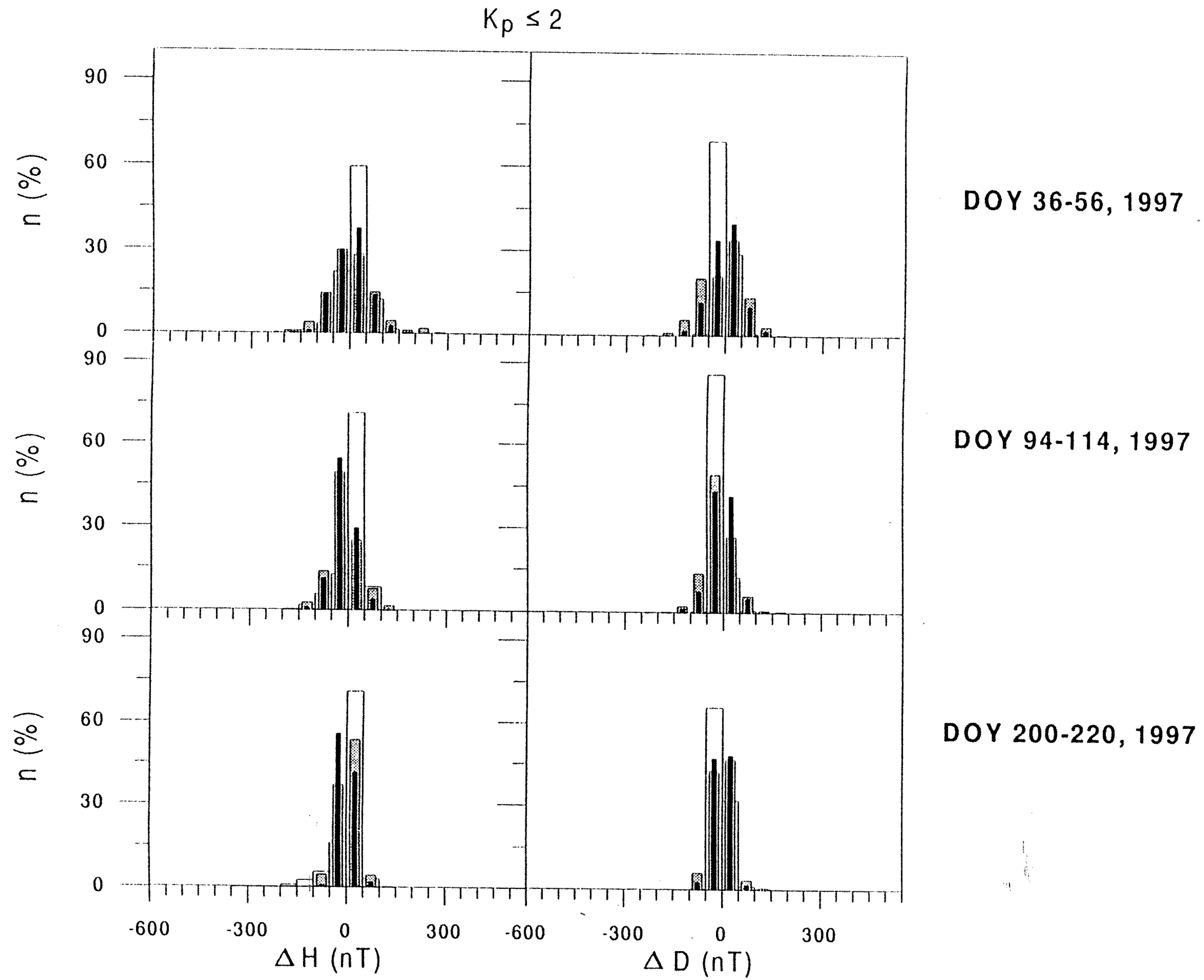
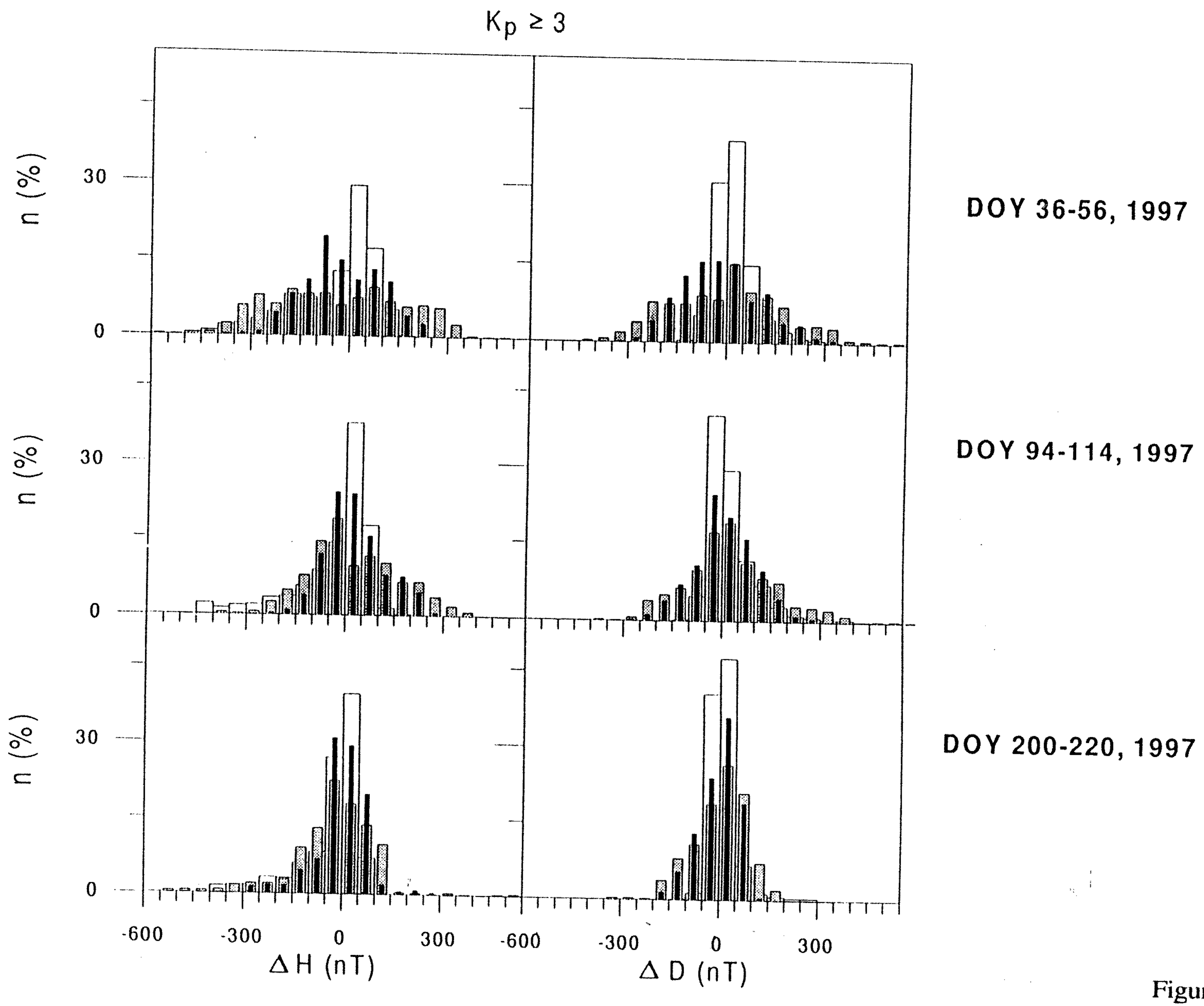


Figure 1.



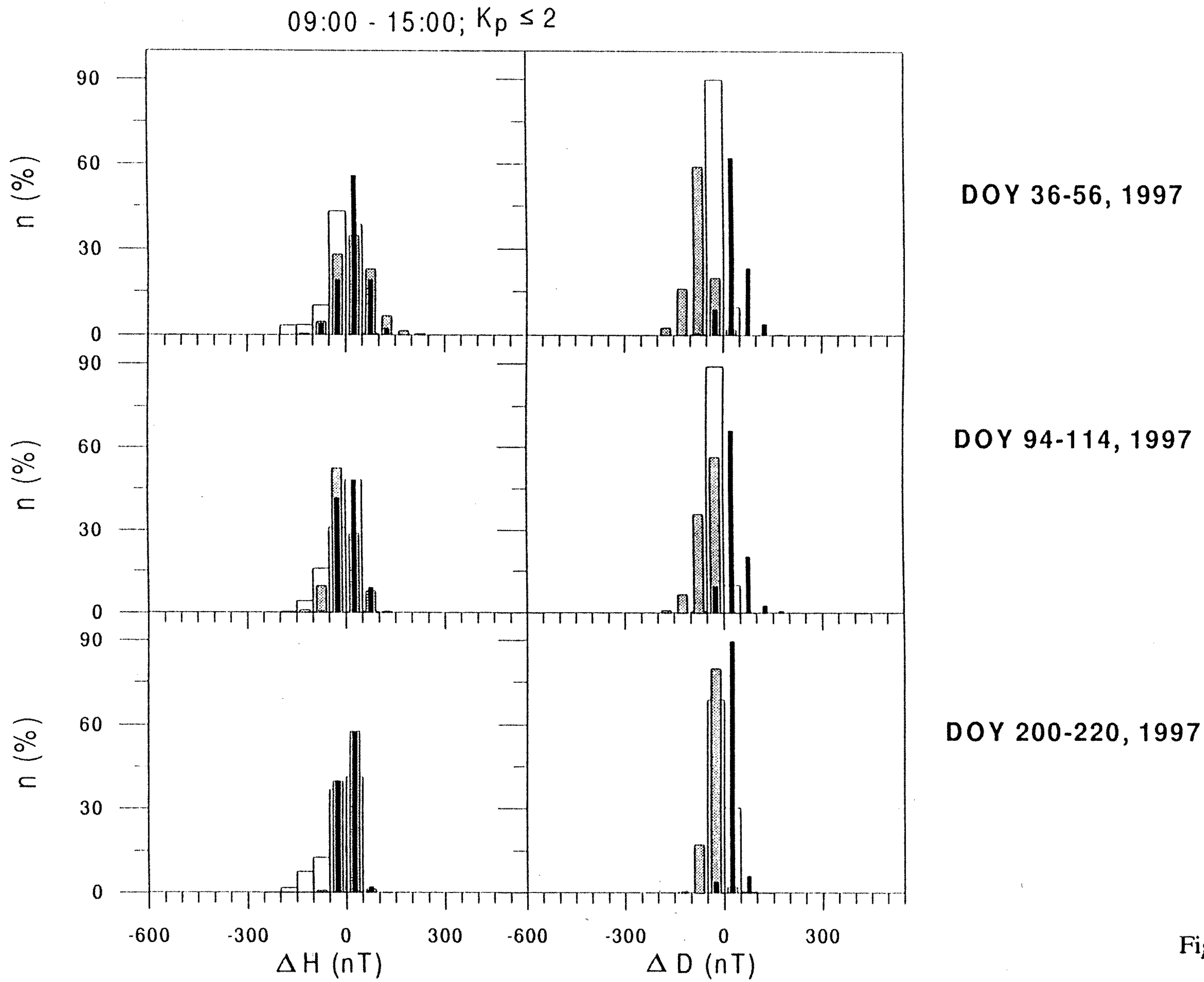
$K_p \leq 2$
n (%)
90
60
30
0
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997
-600
-300
0
300
Δ H (nT)
Δ D (nT)

Figure 2a.



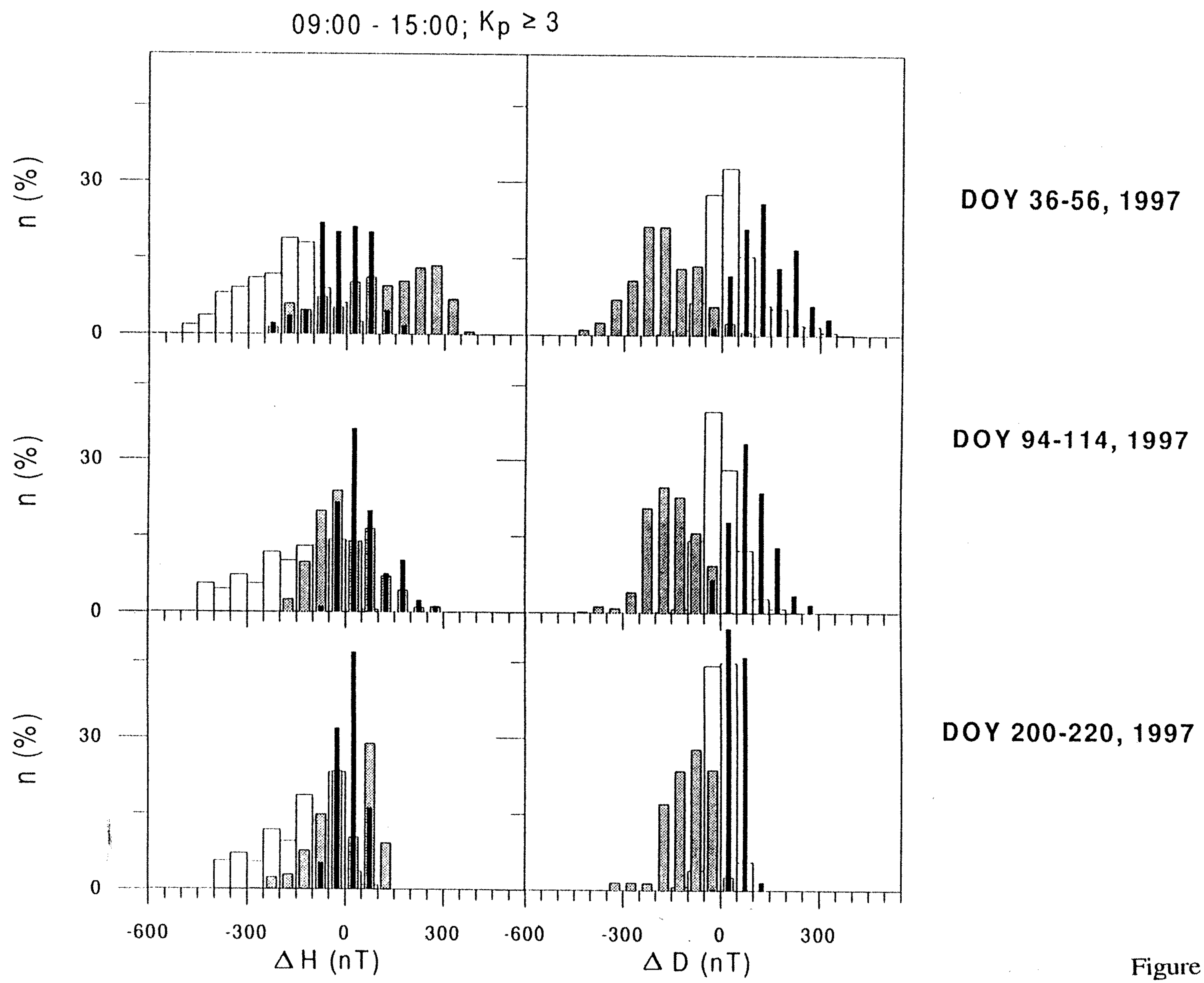
$K_p \geq 3$
n (%)
30
0
n (%)
30
0
n (%)
30
0
-600
-300
0
300
ΔH (nT)
-600
-300
0
300
ΔD (nT)
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997

Figure 2b.



09:00 - 15:00; Kp ≤ 2
n (%)
90
60
30
0
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997
-600
-300
0
300
Δ H (nT)
Δ D (nT)

Figure 3a.



09:00 - 15:00; $K_p \geq 3$
n (%)
30
0
-600
-300
0
300
ΔH (nT)
ΔD (nT)
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997

Figure 3b.

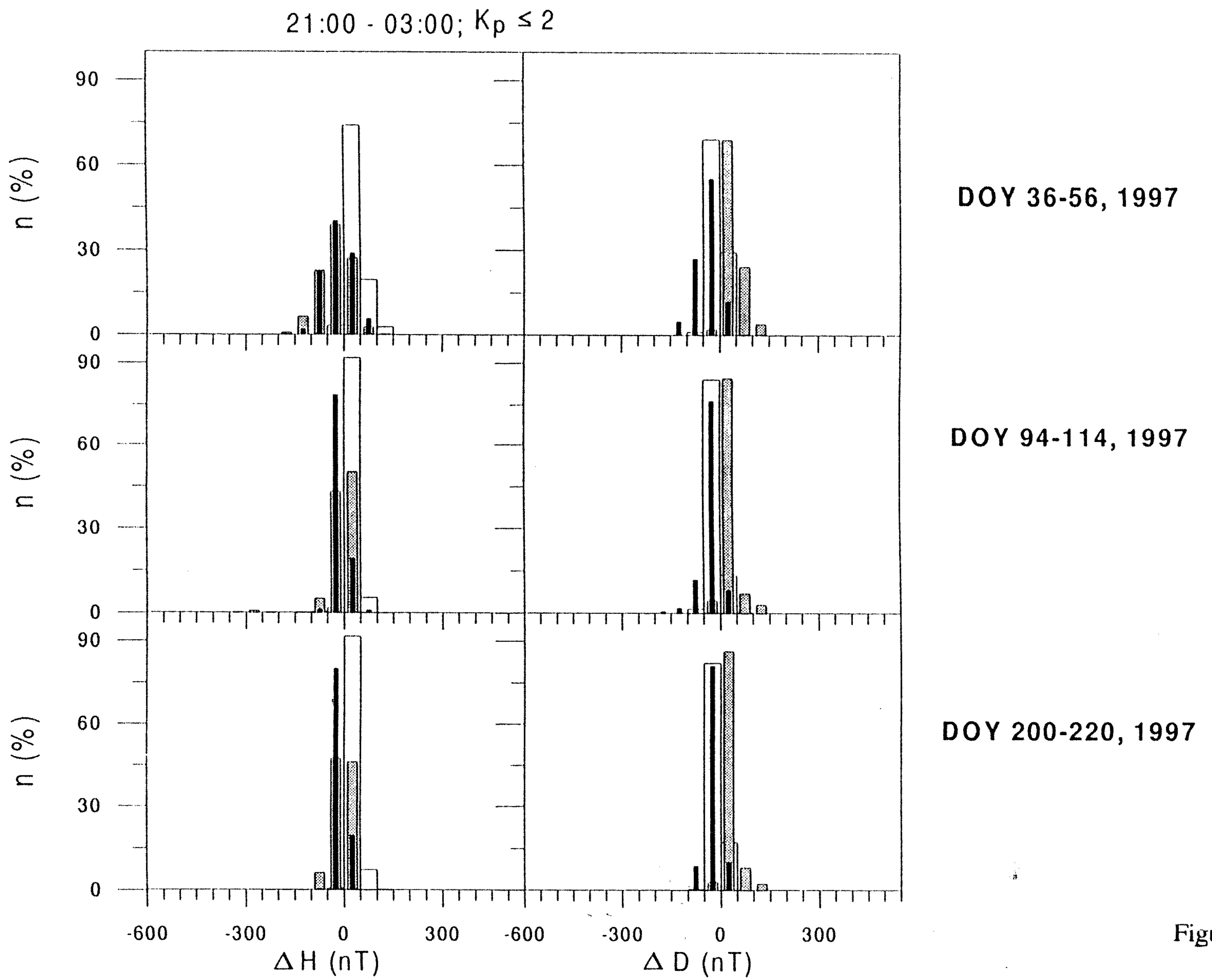

21:00 - 03:00; $K_p \leq 2$
n (%)
90
60
30
0
-600
-300
0
300
ΔH (nT)
ΔD (nT)
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997

Figure 4a.

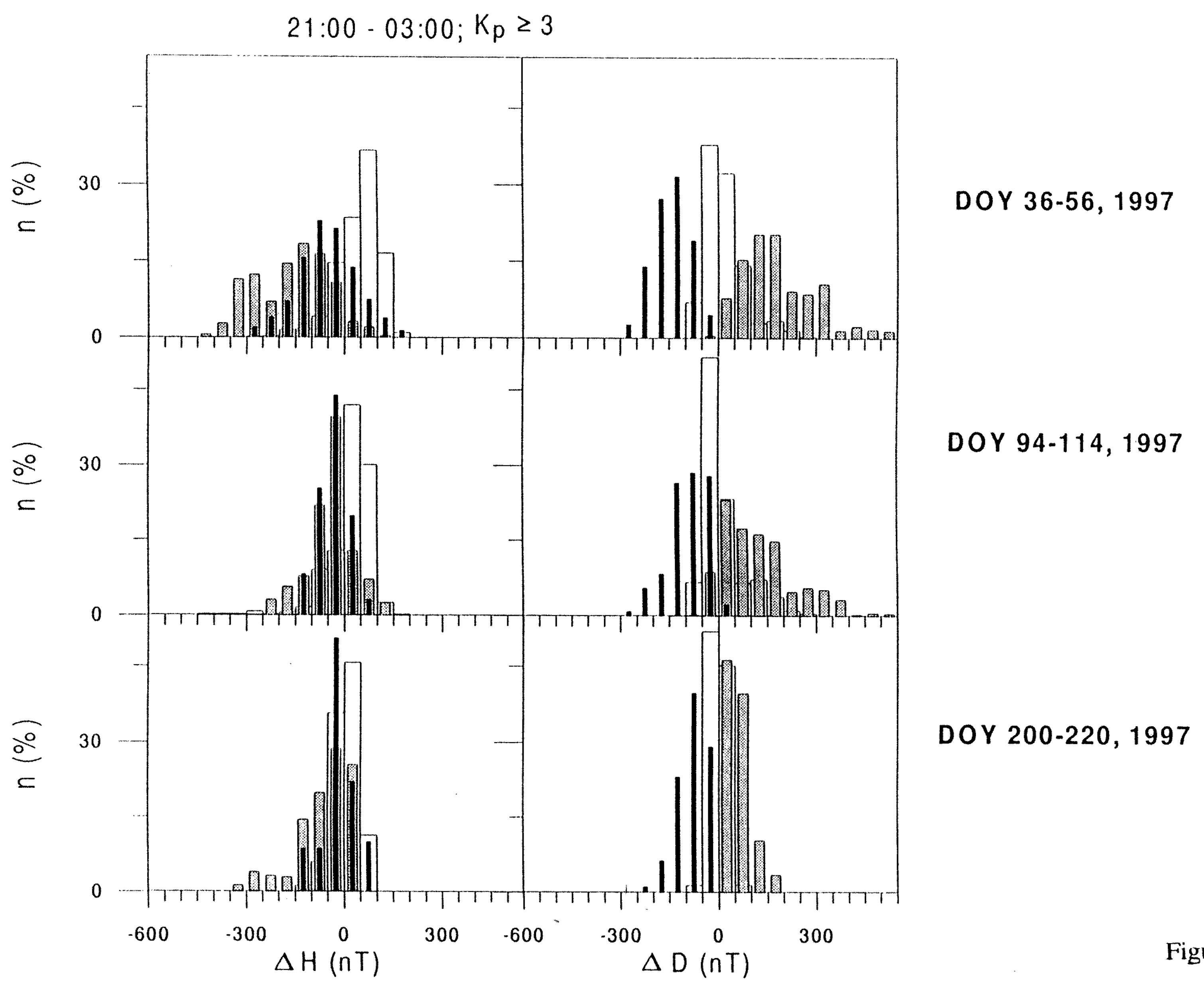

21:00 - 03:00; $K_p \geq 3$
n (%)
30
0
-600
-300
0
300
ΔH (nT)
ΔD (nT)
DOY 36-56, 1997
DOY 94-114, 1997
DOY 200-220, 1997

Figure 4b.